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Author(s): Anna Serotta, Andrew Smyth
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MANAGING CONSTRUCTION-INDUCED VIBRATION IN THE MUSEUM ENVIRONMENT

ANNA SEROTTA, ANDREW SMYTH

ABSTRACT

In the spring of 2012, The Metropolitan Museum of Art began a large-scale renovation of galleries, offices and storage areas in The Costume Institute, which is located directly below the galleries of the Egyptian Art Department. Vibration from construction activities poses a serious risk to museum objects, and the fragile nature of objects in the Egyptian galleries makes this collection particularly vulnerable. To safeguard the collection, a project team including curatorial, collections management, and conservation staff, in collaboration with a group from the Department of Civil Engineering and Engineering Mechanics at Columbia University, worked together to assess the risk to the collection on an object by object basis and developed a range of preventive conservation strategies. This paper will discuss the methods and procedures that were developed not only to protect the artworks but also to allow visitors continued access to as much of the collection as possible during the work period.

Before the renovation, tests were carried out to determine the amount of vibration that would be caused by the demolition of both structural and nonstructural elements in the construction zone. Different tools and demolition methods were tested in various locations to assess which would create the least vibration; at the same time, techniques for mitigating vibration were evaluated. The article discusses the implementation of these mitigation solutions, which included isolation of objects and pedestals with Sorbothane and other vibration-dampening materials. Testing also revealed that shelf design and pedestal shape and material contributed significantly to the degree of vibration amplification. Case studies will be presented that illustrate the response of particular installations to vibration and specific solutions devised for each scenario. For some objects, isolation was not possible; deinstallation decisions and logistics will be presented.

During initial testing, a monitoring system to measure vibration levels and to automatically communicate this information to the project team was developed; this system, which used wireless communication, was implemented throughout the effected galleries before the start of demolition. Automated alerts were sent via e-mail or SMS (text) message to the project team when defined vibration velocity thresholds were exceeded. The corresponding vibration event signals were recorded on a central server for reference and review. The vibration sensors were placed on gallery floors, directly on objects, or on shelves and pedestals and display case decks. The rationale for the general vibration thresholds used in the project, which were adjusted depending on the sensor location and context, is discussed. The quantitative feedback provided by the vibration monitoring system was augmented with daily observation and regular hands-on assessment of vibration levels throughout the two-year project.

Although much information was gained through limited initial testing, the actual construction project often produced unexpected vibration and consequently mitigation solutions had to be adapted. Preliminary observations about the response of objects, installations, and the building itself to various demolition and construction activities will be shared. The dynamic nature of the construction project required great flexibility, and constant dialogue between all members of the project team, the construction department, and contractors was essential to the overall success of this project.

1. PROJECT OVERVIEW AND CHALLENGES

From the spring of 2012 until the end of 2013 The Metropolitan Museum of Art conducted a large-scale renovation of The Costume Institute, which is located directly below the galleries of Egyptian Art. The project included a complete renovation of Costume Institute storage spaces, gallery spaces, offices, and conservation labs and involved the demolition of both structural and non-structural elements and the installation of new walls, ductwork, and architectural features.

To safeguard this very fragile, ancient art collection, a project team including curatorial, collections management, and conservation staff worked together with the museum's construction department in collaboration with a team from the Department of Civil Engineering and Engineering Mechanics at Columbia University. The main goals of the project team were to assess the risk to the collection from construction-induced vibration and to develop a range of preventive conservation strategies. This article serves as a preliminary description of the project for timely dissemination. A more comprehensive article manuscript is in preparation from the authors together with other key project team members.

The area above the construction work zone consisted of 27 galleries housing over 20,000 objects, which are, on average, between 2000 and 4000 years old. Objects in the collection are both organic and inorganic, representing the full spectrum of materials used in ancient Egypt including stone, metal, ceramic, glass, basketry, linen, and wood; extremely fragile organic materials such as mummies, ancient foodstuffs, and dried flowers are found throughout the collection. There are other factors contributing to the vulnerability of these objects. Many are made of composite materials, such as plastered or painted wood, and they often contain ancient joins such as wooden dowels, ancient glues, or rawhide ties. As this is an archaeological collection, much of which came to the museum in the early 20th century, many objects contain old restoration materials, which are often undocumented. For these reasons, the collection of Egyptian art is one of the most fragile collections the museum, and the interaction between the various components of the objects when exposed to vibration was of particular concern for the project team.

The gallery installations themselves also presented a challenge. Many of the installations are old, dating to the late 1970s and early 1980s; and some of the large and very fragile objects have not been moved since they were put on display decades ago. Additionally, a large part of the collection is housed in study-storage galleries, which contain thousands of objects. About 90% of the collection is on view, and there is only permanent storage space for the remaining 10% of the collection.

Given these challenges, it was critical at the outset to assess how vulnerable these objects and installations would be to construction-induced vibration so that appropriate preventive strategies could be implemented.

2. WHY DO VIBRATIONS MATTER IN THE MUSEUM CONTEXT?

Vibrations can be the cause of damage to objects during short or long-term exposure. These can cause increased stresses (bearing, bending, shear, etc.) that can damage objects. Because vibrations are a type of cyclic loading, they can cause fatigue damage (like a paper clip that snaps after bending it back and forth). Vibrations can also cause the growth of existing cracks.

2.1 VIBRATION BASICS

Although it is beyond the scope of this short article to provide a comprehensive review of the basics of mechanical and structural vibrations, an extremely brief summary of some fundamental elements is useful to provide a framework for the discussion. Numerous texts, for example Rao (2004), are available, which cover the fundamentals of vibrations. Anything that has mass and some flexibility (the reciprocal of stiffness) can vibrate. The frequency at which things tend to vibrate is related to the square root of the stiffness over mass; for example, for a given stiffness of a shelf, extra mass will make it vibrate at a lower frequency, and vice versa.

In the context of a museum under construction it is, of course, not just shelves which vibrate, but everything from the building itself, responding to impact and other demolition tools, all the way down to vibrations occurring within an object. It is, however, useful to focus on the simple (and yet, in the museum context, intrinsically important) example of the cantilevered shelf, as shown in figure 1a. If the wall to which it is attached is vibrating vertically with displacement $x_s(t)$ then we might be interested in how much the shelf vibrates $x_{tip}(t)$. In general, these will not be equal.

The surprising thing to the uninitiated is that the shelf vibrations may be much larger than the exciting wall vibrations. This is due to the well-known resonance condition that occurs when the exciting frequency is near the natural frequency of the shelf. This is shown in the amplification plot (fig. 1b) for

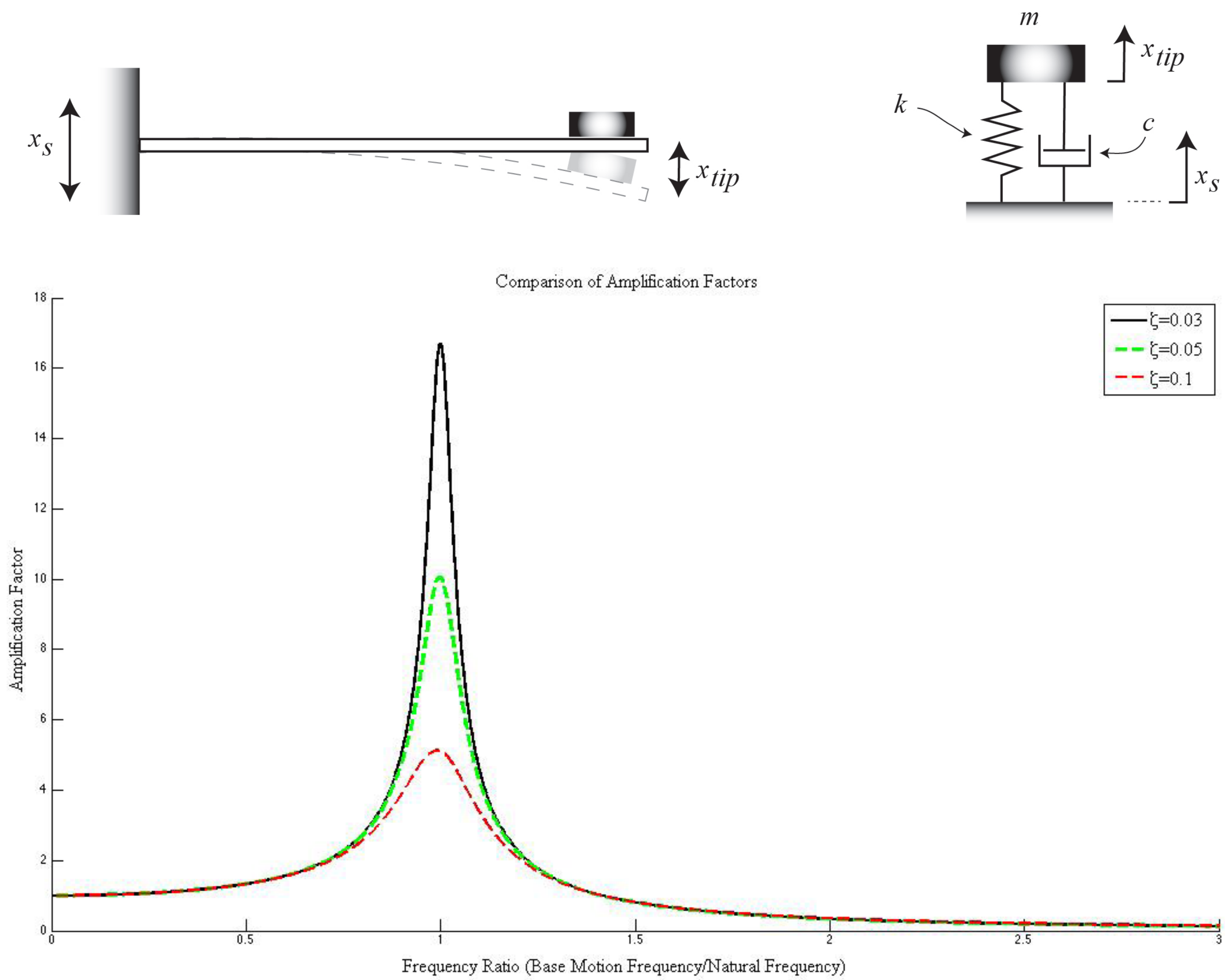

Fig. 1 (a) Schematic of simple cantilevered shelf system with vertical wall excitation, (b) The amplification of a simple "single degree of freedom" dynamic system due to harmonic excitation. The horizontal axis in the graph is a ratio of the harmonic excitation frequency to the natural frequency of the system. (Courtesy of Andrew Smyth)

the same shelf with different values of inherent energy dissipation (or damping). Notice that even for a relatively large damping value of 0.1, the response can be five times as large as the excitation displacement. As the frequency of excitation goes higher above the natural frequency of the shelf system, the response starts to drop significantly. This idea will be used later.

One of the key consequences of this is that when considering all of the objects and mounts, and pedestals (all of which have their own natural frequencies and damping values), it becomes challenging to anticipate an acceptable level of input excitation because it is hard to anticipate the respective responses of the objects.

2.2 VIBRATION THRESHOLDS

For practical matters, however, it is important to have some reference values to use as guidance to judge vibration levels and to distinguish between the excitation (in the museum context at the floor or in the wall) vibration and the response vibration levels. Velocities are often used as a standard for vibration levels for a variety of reasons. Note, however, that accelerometers (which measure accelerations) are typically used to make measurements. To start, one may consider a review of vibrations standards such as that presented in S.S. Rao's textbook (2004) *Mechanical Vibrations* highlighting different vibration standards including a discussion of human perception thresholds. According to ISO 2631, the human perception curve begins at about 1 mm · s^{-1} at low frequencies. There is also an ISO DP4866 standard that has a minimum threshold starting at 3 mm · s^{-1} for building structural damage.

Although this article does not delve into a detailed comparison of different standards that have been used, one may simply say that one should be cautious when borrowing from standards that were developed for very different contexts to primarily protect single-family homes from damage due to construction blasting vibrations. Many of these permit an increase in velocity threshold above 10Hz. See, for example, Johnson et al. 2013.

In a hypothetical comparison, one may have a situation where a single story house (for which many of the standards were designed) and museum objects are far apart; for example, a single-story house might be expected to have a natural frequency in the 4–12 Hz range, whereas a museum object or mount may have a natural frequency in the 20Hz range; one can see that it may be ill-advised to permit more energy in an area ($>$ 10Hz) where amplification may be the greatest for the object or object mount. Not knowing exactly where the amplification may be greatest for our museums and our objects is why measurements are made.

3. DEVELOPING STRATEGIES FOR VIBRATION MITIGATION AND MONITORING

To better understand the effects of different tools on this specific building with objects displayed as they were, a series of pilot tests were performed before the demolition and construction phase of the project. These pilot tests were initially planned by the museum's construction department to provide more information about the building and were conducted at different locations throughout the work zone. The goal of the project team was to determine the amount of the vibration that would be caused by the demolition of both structural and nonstructural elements in the area of the Costume Institute, and different tools and demolition methods were tested in various locations to assess how much vibration each would produce. Additionally, this testing helped identify which installations in particular were more susceptible to vibration and provided an opportunity to test mitigation and monitoring strategies.

3.1 MEASURING VIBRATION IN THE GALLERIES

The vibration measurement instrumentation used for the pilot phase was very similar to the setup for the demolition and construction phases, although pilot testing was primarily done during time when the museum was closed, so aesthetic considerations were not important. During the actual construction phase, a wireless system of data communication was employed.

Figure 2 illustrates a schematic of the monitoring network. Accelerometer sensors were connected to wireless data acquisition nodes, as seen in figure 3, which would communicate with a central processing server over the museum's own wireless network. Data were analyzed in real-time and when thresholds, which had been established from the pilot testing phase, were exceeded, automatic warnings were sent via e-mail and text message to key individuals on the engineering, construction, and conservation staffs. Typical alert thresholds were in the 1 or 3 mm · s^{-1} range. Note that these were not necessarily thresholds that would cause work stoppage, but were used as levels that would trigger alert messages that were reviewed in the appropriate context, and which, in turn, led to different actions being taken. Alert thresholds were often programmed for different sensors depending on their location (e.g., floor or shelf) and the perceived fragility of nearby objects. Wireless nodes were installed throughout the

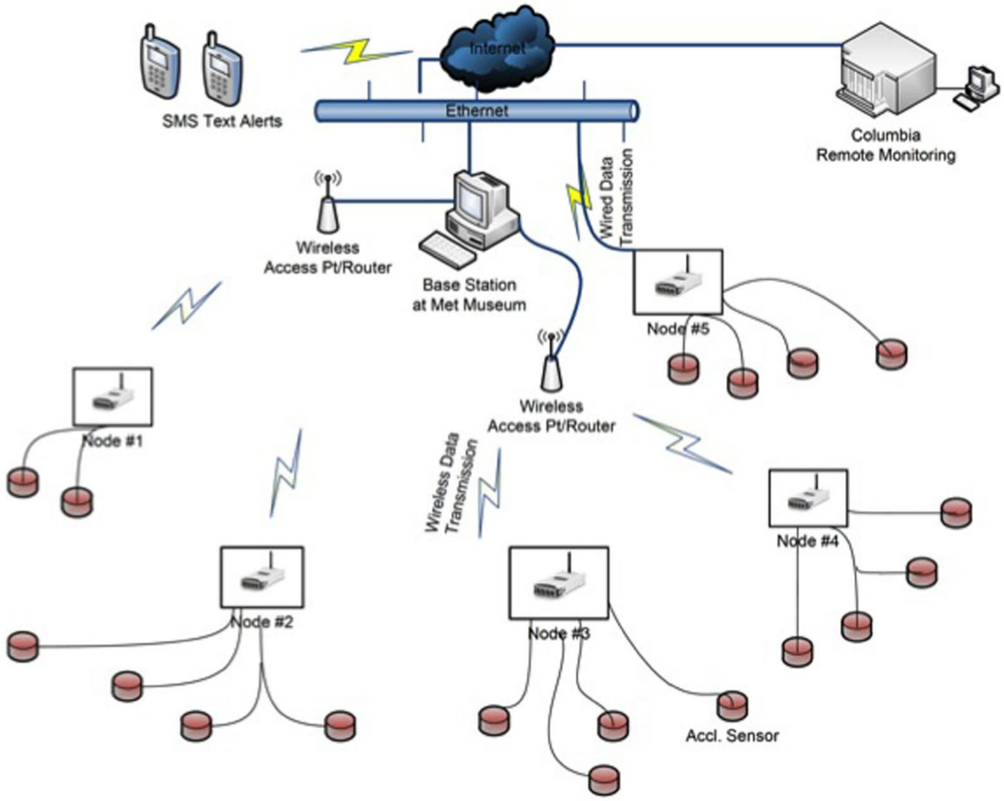

Fig. 2. Schematic of wireless monitoring network developed by Columbia University team (Courtesy of Andrew Smyth)

Fig. 3. Wireless data acquisition unit with sensors attached (Courtesy of Andrew Smyth)

Fig. 4. Sensor placement during pilot testing (Courtesy of Andrew Smyth)

galleries above the work zone for the duration of the project; sensors were often positioned on or near fragile objects or installations that might amplify vibration. Additionally there were some "roaming" units used by the museum staff to concentrate on specific areas as the demolition and construction activities moved from area to area. Wireless nodes were often installed in the light attics above the cases to utilize power from the lighting system. Case lights were switched on and off at set times each day, so that the monitoring system was running well in advance of the contractors' work day.

3.2 OBSERVATIONS MADE DURING PILOT TESTING

During the pilot testing, sensors were placed on the floor, on pedestals and shelves, and on the objects themselves with Mylar barriers (fig. 4).

During the pilot testing phase, the data were analyzed directly on a laptop "dashboard" by the Columbia team on site, and real-time vibration data were communicated to the project team, who used their hands to correlate numerical data with what they actually felt on pedestals and objects.

Some general observations were made during the pilot testing, which helped the project team and contractors to select the tools and methods that would produce the least vibration while still being able to accomplish the task at hand. Large vibrations were recorded due to heavy impact tools such as sledgehammers and crowbars, and it was agreed that these tools would not be used in the demolition process. In contrast, a light chipping gun produced generally acceptable levels of vibration, and instead of shooting anchors into ceilings for piping, a high-speed coring drill produced much less vibration. As expected, cantilevered shelves used to display small objects in many galleries significantly amplified vibrations.

3.3 VIBRATION MITIGATION STRATEGIES

3.3.1 Isolation with Sorbothane

Along with recommendations for equipment and methods, the pilot testing also provided valuable information on vibration mitigation strategies. One of the steps taken to reduce the potential of damage to the artifacts was to decrease the natural amplification of the vibrations that occur in the art.

Fig. 5. Testing Sorbothane isolation during pilot tests. Sorbothane pads are installed under the coffin bottom but not under the lid. Vibration responses were measured in both the coffin bottom and lid, and also in the floor. (Courtesy of Andrew Smyth)

Fundamentally, this involves the mechanical decoupling of the vibration source (often the floor) from the object by means of a very soft viscoelastic layer, which performs as a kind of filter. This was accomplished by introducing Sorbothane, a viscoelastic urethane polymer that comes in a variety of hardnesses and thicknesses. The core concept of how Sorbothane works is that it provides a soft layer that mechanically tends to isolate the object it supports. From a vibrations perspective, this has the effect of creating a low natural frequency system with a frequency (if properly designed) significantly lower than the excitation frequency. The result is a substantially decreased object response motion.

Figure 5 demonstrates the use of Sorbothane to decrease the response vibrations in a standing coffin base when excited by a 30 lb. chipping gun removing concrete fireproofing on a beam just beneath the floor.

The response of this coffin was compared with vibration levels in the adjacent floor and in the lid of the coffin, which had not been isolated with Sorbothane (fig. 6).

The objects were exposed to vibration from the chipping gun for a short duration, and the response vibrations were recorded. In this instance, Sorbothane was a decidedly effective isolator: the velocity reduction between the floor and the isolated coffin base was approximately 75–80%. Other objects isolated with Sorbothane also performed well during the probes, showing vibration reduction factors of 3, 4, and 5 with the appropriately designed Sorbothane pads, and these results encouraged wider use of the material.

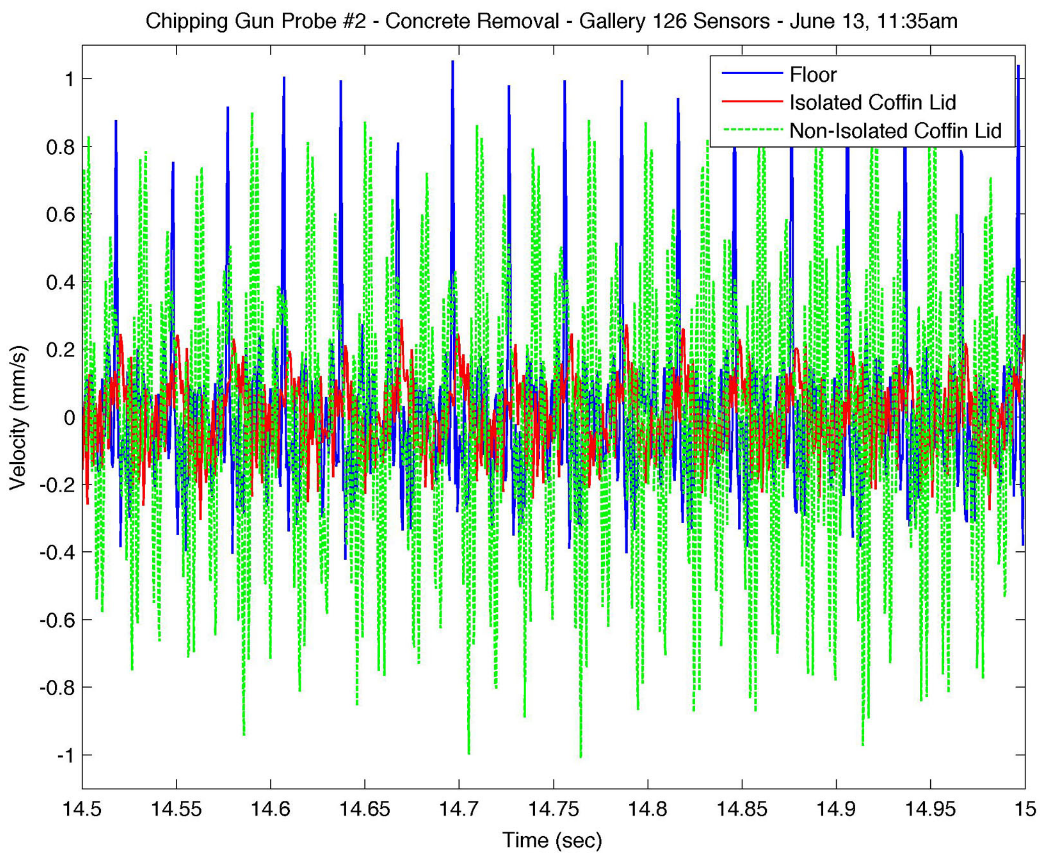

Fig. 6. A comparison of the response of the floor, with a nonisolated coffin lid and a similar neighboring coffin (Courtesy of Andrew Smyth)

The project team installed Sorbothane under a variety of objects and pedestals, particularly in galleries above areas slated for structural demolition. One pad was typically placed in each corner of the base of the object or pedestal, although rectangular bases often required additional pads below their longer edges. To ensure good performance, it was important to achieve an even distribution of weight on all pads. If an even distribution of weight was not possible because the bottom surface of the object was uneven and the object had no pre-existing base, boards of high density polyethylene (HDP) were inserted between the object and the Sorbothane pads (figs. 7a, 7b).

Choosing the correct pads for the specific object is critical, and the wrong choice can actually make things worse; for example, the system cannot be softened too much, otherwise the Sorbothane will creep: flattening over time, which renders it useless. The Columbia University team developed a customized simple software tool for the museum conservators so that they could appropriately design their Sorbothane pads for each object. This allowed them to insert maximum pad thickness (for aesthetic reasons) and provided limitations on the strain level to prevent creep. The software was created as a design tool to help museum staff determine pad dimension and property selection. The resulting calculations match those of the manufacturer-created software tool, which could be used in a trial-and-error mode to achieve the same results.

Pedestals, rather than individual objects, were isolated when the objects themselves were particularly fragile or when the objects themselves were not heavy enough to properly compress the Sorbothane pads. (Recall that because one is trying to create low natural frequency systems when performing isolation, it is important to have a relatively large mass to stiffness ratio.) One group of fragile, lightweight objects was effectively isolated by increasing the weight of each object with a steel

Fig. 7. (a) Sorbothane pads were installed in each corner of the HDP board and (b) the object was placed on top of the HDP board (Courtesy of Anna Serotta)

plate base. These objects, painted wooden models from the tomb of Meketre (MMA 20.3.9-.13), were previously installed on pedestals whose mushroom-shaped structure precluded effective isolation; the bases of these pedestals were relatively narrow and the additional height of the Sorbothane pads would have positioned the objects too close to the top of their case. New, shorter pedestals were designed and the objects were reinstalled on Sorbothane pads on top of these pedestals, with a steel plate positioned between each object and its Sorbothane pads. This new configuration, shown in figure 8, enabled the effective isolation of the models and allowed these highly popular objects to remain on view for the duration of the project.

This mitigation method had to be further modified for another group of objects in the same gallery, the Meketre boats (MMA 20.3.1-.6), which sit on glass cantilevered shelves. As with the Meketre models, deinstallation of these objects was seen as a last resort because of their importance, popularity, and fragility. Sorbothane pads were tested under one of the Meketre boat models during the pilot tests, and the vibration responses of the isolated boat and shelf were measured. The cantilevered shelves acted as

Fig. 8. (a) Sorbothane pads installed under steel plates (Courtesy of Andrew Smyth); (b) the Meketre models isolated on their new pedestals (Courtesy of Gustavo Camps)

a low-pass filter for the input vibrations, effectively filtering out much of the high-frequency component. Not surprisingly, those low frequency input vibrations were amplified, rather than dampened by the Sorbothane pads, where the response of the isolated boat is significantly greater than that of a nonisolated boat. In this case, where low-frequency vibrations were expected, alternative steps had to be taken to reduce the magnitude of the response vibrations. The solution developed by the project team was to install a support leg in the front corner of each shelf, as seen in figure 9. The legs helped elevate the natural frequency of the shelf support system and thus reduced shelf movement and, in addition, the Sorbothane pads installed between each leg and the shelf served to further dampen vibration. This system was tested and found to satisfactorily reduce the vibration experienced by the fragile boats.

Steps were also taken to mitigate vibration in entire galleries. In the same gallery containing the Meketre boats and models, a tuned mass damper was installed. This consisted of two large weights (in

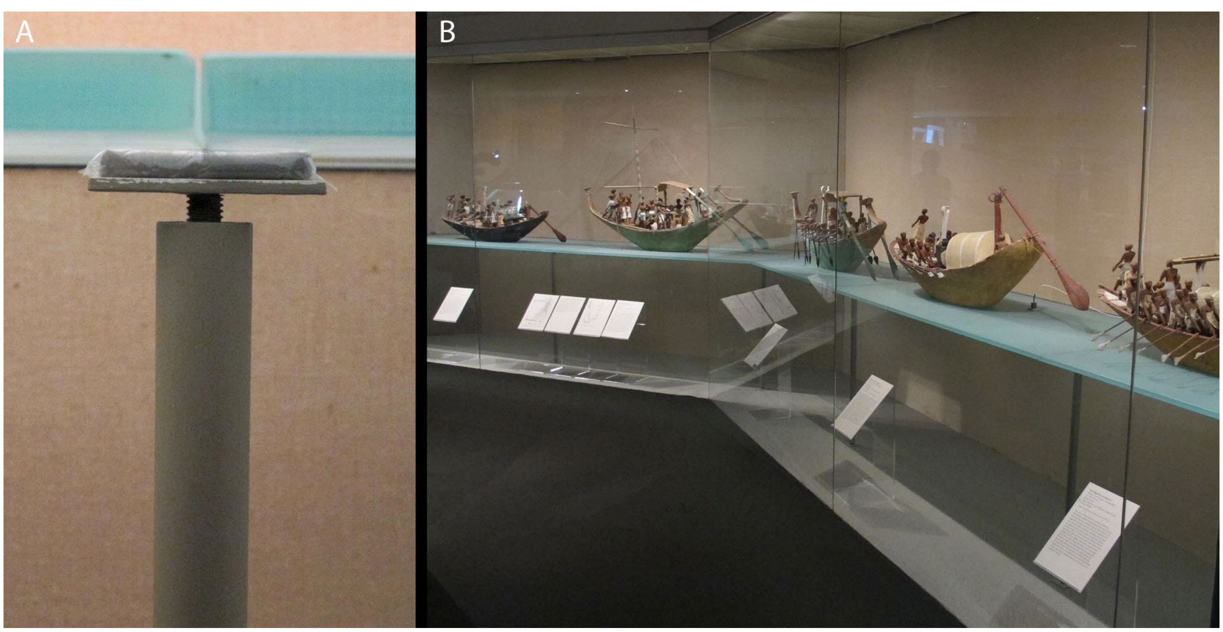

Fig. 9. (a) Sorbothane pads inserted between support leg and glass shelf; b) Support legs with Sorbothane pads at their top ends were installed under cantilevered glass shelf with Meketre boats (Courtesy of Andrew Smyth)

this case granite pedestals) placed onto Sorbothane pads in the center of the gallery. The Sorbothane/ weight system was tuned to coincide with floor vibration frequencies so that during construction the vibration of these weights would dissipate the energy of the floor vibrations. This system was tested and found to be another effective vibration dampening solution. Lower-cost versions of the same system were installed in closed galleries using cast concrete blocks.

3.3.2 Other Mitigation Strategies

Although the project team generally found Sorbothane to be a useful tool for vibration mitigation in the galleries, there were many objects whose size, shape, weight, or mounting system prevented effective isolation with Sorbothane. In such cases, objects were often protected from vibration in situ with other cushioning materials, such as polyester batting, polyethylene foam and tissue. These padding materials were installed in both galleries that would be closed for the duration of the project and in galleries that would remain open. In some cases, an entire shelf was covered with polyester batting and the objects were reinstalled over a tissue layer to protect particularly delicate materials from catching on the batting fibers. Although these materials are not particularly designed for vibration isolation, they proved to be very effective at cushioning and protecting small, lighter objects.

Another solution for protecting small, light objects was to reinstall entire shelves on trays made from thick archival blueboard and thin polyethylene foam, as shown in figure 10. These trays were given

Fig. 10. Small objects reinstalled on foam trays (Courtesy of Anna Serotta)

Fig. 11. Bumpers installed in a closed study gallery to prevent objects from walking off of shelves (Courtesy of Anna Serotta)

additional foam rims, which prevented vibration from causing especially light objects from walking off of shelves.

Because making and installing thousands of tiny objects on to the foam trays was time consuming, in closed galleries, bumpers made of Ethafoam tri-rod were often substituted (fig. 11). Bumpers were used only in cases where the objects were not particularly fragile and where the major concern was the objects walking off of their shelves.

Although many of the strategies developed were repeatable for a variety of object types, risk assessment and mitigation planning had to be carried out on an object-by-object basis, taking into account the structure and condition of the object, the mounting/installation system, and the type of demolition/construction work to be performed in that area.

3.3.3 Storage Solutions

For many objects, vibration mitigation was not possible. Either vibration in a particular area was deemed too high for effective isolation, or the mounting system or object itself prevented isolation. Additionally, the implementation of mitigation strategies was time-consuming, and the scope of objects needing protection widened as more information was gleaned about the vibration behavior of the building, installations, and objects; thus, for many objects, deinstallation was the best solution.

To accommodate the deinstalled objects, the Egyptian rotating exhibition space was converted into a temporary storage space. On the basis of the initial tests, specific objects that could not be safely isolated were slated for deinstallation, but the project team was also concerned about vibrations that might be stronger than that produced during the tests or any unexpected behavior of objects and mounting systems when exposed to vibration. To plan for any unanticipated deinstallation, the shelving size and layout of this temporary storage space was planned to accommodate a large range of objects.

It was decided to close all of the study galleries for the duration of the project and to use them as in situ storage; most objects in these galleries were rehoused with the cushioning materials described in section 3.3.2. Door plugs and scrims were created to block entrance to these spaces. The scrims were printed with a note explaining why the gallery was closed. Keeping the objects that could be safely nested in the galleries allowed the team to reserve precious storage space for the objects that did need to be moved, and minimized unnecessary object movement.

4. MONITORING AND COMMUNICATION DURING CONSTRUCTION

Although the accelerometer monitoring system was able to give us information about vibration levels in very specific locations, in-person monitoring was also required for the duration of the project. As demolition work progressed, it was noted that vibrations were often very localized and would be registered only by a sensor in the immediate area of the impact; therefore, it was critical to closely monitor locations without sensors when demolition or construction work was being carried out in these areas. Conservation and Egyptian department staff members also routinely took a hands-on approach to monitoring, particularly during structural demolition or when work was being carried out below particularly fragile objects. Team members used their hands to feel how the objects themselves were responding to vibration, noting which objects amplified vibration levels and adjusting mitigation strategies accordingly.

Additionally, Egyptian department staff members performed a daily visual check of each gallery. Before the start of demolition, conservators identified especially fragile objects in each gallery and wrote a guide for the monitoring team that outlined both general considerations and specific issues of concern in each gallery. Many fragile objects were also photographically documented before and during project. Staff members conducting the daily monitoring alerted the project team members with any concerns, and condition issues were addressed by members of the conservation staff.

Regular monitoring was particularly important for objects like some of the more fragile coffins, which were not able to be isolated with Sorbothane or other cushioning materials. The configuration of the mounts of these coffins (cantilevered shelves or four-legged brass stands) made the installation of Sorbothane pads complicated, and it was decided that handling these extremely fragile objects, all of which are constructed from multiple pieces of ancient wood with friable gesso and paint layers, could potentially cause more damage than vibration. As these coffins were not directly over areas where structural demolition was planned, it was agreed that they would be closely monitored for the duration of the project; if vibration levels exceeded acceptable limits for a sustained period of time or if the team determined the safety of the objects to be compromised, then the solution of leaving them in place would be reevaluated. Before the start of demolition work, conservation staff members carried out an object-by-object condition assessment, documented fragile surfaces with high-resolution photos, and also carried out some minor consolidation treatments of particularly friable surfaces. White paper was put under objects in closed galleries to better observe any powdering or flaking paint or wood, and a tuned mass damper was installed in the gallery.

Demolition work began in April 2012. Work was divided in to three phases: "heavy demolition" (removal of structural elements), "light demolition" (removal of nonstructural elements), and construction (installation of new elements). Faced with time constraints and thousands of objects remaining to isolate or deinstall, the project team worked with the contractors and the construction department to devise a seven-phased solution for light demolition activities, which were slated to begin first. Rather than working in multiple areas simultaneously, the contractors would work in one area at a time, completing the work in one area before moving on to the next. This phasing plan helped the project team to focus mitigation and monitoring efforts.

The museum's construction department provided the project team with continually updated work scopes and plans, and also with the tools we needed to communicate with the contractors. The team prepared an internal schedule for responding to alerts and for communicating with the contractors. It was agreed that no work would occur outside of regular museum staff hours so that any incidents could be dealt with by the appropriate personnel.

5. SUMMARY AND CONCLUSIONS

Overall, this multifaceted project spanned approximately 33 months, from initial planning meetings in February 2011 to the official completion of the construction project in December 2013. The first round of pilot testing commenced in June 2011 and preparation of the collection followed immediately after and lasted through the spring of 2012, with additional mitigation activities undertaken as needed for the duration of the vibration-creating work, which lasted until August of 2013.

Over the course of the project, over 14,000 objects were isolated with Sorbothane or other support materials or moved to storage. Vibration mitigation with Sorbothane was highly effective, although correct installation was found to be critical, and the performance of the material over time had to be carefully monitored. When Sorbothane isolation was not appropriate, Ethafoam, batting, tissue, and other cushioning materials were also found to be effective at dampening vibration.

Although approximately two-thirds of the collection usually on display was off-view (a large percentage of this number being objects in the study collections), many collection highlights, such as the Meketre boats and models, were able to remain on view for the duration of the project. The extensive use of Sorbothane in the Late New Kingdom and Third Intermediate Period coffin galleries allowed these large, fragile objects to remain in place despite their proximity to major structural demolition. Objects in closed galleries were often able to be protected in situ, alleviating the inherent risk in transporting fragile objects and allowing the team to conserve valuable storage space.

No major damage to any artwork was incurred from vibration. As expected, the most prevalent condition issue was minor crumbing and powdering of friable wooden substrates and gesso layers. Debris was documented and removed by conservation staff, and additional treatment was carried out when necessary. Despite the support leg solution for the Meketre boat shelf, demolition work below this area produced vibration levels that were higher than expected, causing the failure of an old join in one wooden figure.

Perhaps the most dramatic incident was the migration of small objects on a cantilevered shelf in one of the study galleries. Work under this area produced significantly more vibration than anticipated, causing objects on shelves directly above to be significantly displaced. Fortunately, these objects were prevented from walking off of the shelves by previously installed Ethafoam tri-rod, and more fragile objects were protected with tissue and foam supports.

Throughout the testing, preparation, and construction phases of the project, museum staff learned a great deal about how objects and installations respond to vibration, and also how vibrations travel and change within the architecture of the building. Several critical observations were made about the behavior of particular installations and, in future, the project team might advise against placing particularly fragile objects on vibration-amplifying cantilevered shelves and Plexiglas pedestals, particularly if vibration-producing activities are anticipated. Vibrations were frequently stronger than anticipated (often stronger than vibration levels recorded during the probes) and sometimes traveled in unexpected paths, being dampened or amplified by the various materials in gallery floors and walls. The same type of work or tool could produce different vibration levels from one area to the next, and occasionally vibration traveled significant horizontal and vertical distances. On the other hand, some construction activities resulted in very localized vibration that was often not detected by nearby sensors. Unforeseen vibration events also arose, as one might expect, from incidents in the construction zone and from regular museum activities, such as opening case doors, rigs driving through the galleries, or visitor traffic and accidents.

Real-time vibration data communicated by the sensors were critical to the project team's ability to respond to vibration events in the galleries, but for the aforementioned reasons, and because the objects themselves sometimes amplified vibration, monitoring could not be done through numerical data alone. In-person observation was a critical component of the project; this, in combination with the extensive preparatory work, was a considerable strain on the available workforce and required significant coordination efforts.

In general, the project's success was largely thanks to effective communication between museum staff, engineers, and contractors. The work schedule changed frequently, and all parties needed to remain flexible. Weekly meetings, regularly distributed work schedules, and constant dialogue ensured that demolition and construction work could move forward while ensuring the safety of this important collection.

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SOURCES OF MATERIALS

Sorbothane (aka. Ultra-Soft Polyurethane) in a variety of thicknesses and durometers
McMaster-Carr
PO Box 440
New Brunswick, NJ 08903
732-329-3200
www.mcmastercarr.com

Ethafoam, Acid-free Tissue, Mylar, Blue Board (Heritage Courrugated B-Flute Board) and Pellon (non-woven polyester batting)
Talas
330 Morgan Ave.
Brooklyn, NY 11211
212-219-0770
www.talasonline.com

Ethafoam Tri-rod (aka. GripStrip Backer Rod)
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Charlestown, IN 47111
877-275-2739
http:/weatherall.com

Accelerometers
PCB Piezotronics, Inc.
3425 Walden Avenue
Depew, NY 14043-2495
800-828-8840
www.pcb.com

High Density Polyethylene Sheets
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PO Box 440
New Brunswick, NJ 08903
732-329-3200
www.mcmastercarr.com

ANNA SEROTTA graduated from the Conservation Center, Institute of Fine Arts, New York University, in 2009, where she majored in objects conservation with a focus on archaeological materials. After graduating, Serotta completed a fellowship in the Sherman Fairchild Center for Objects Conservation at the Metropolitan Museum of Art. Between 2010 and 2014, Serotta held the position of Contract Conservator and then Assistant Conservator in the Sherman Fairchild Center for Objects Conservation at the Metropolitan Museum of Art, working predominantly with the Egyptian Art collection. In addition to her museum work, Serotta participates regularly in archaeological fieldwork; currently, she is the senior field conservator at the Met's excavations at Dahshur in Egypt and New York University's excavations at Selinunte in Sicily. She is also an adjunct professor at the NYU Conservation Center, where she coordinates and lectures in a short course in archaeological field conservation and co-teaches a course on conservation documentation. Address: 40 Sidney Place, Apt 2B, Brooklyn, NY 11201. E-mail: aserotta@gmail.com

ANDREW SMYTH is a professor of civil engineering and engineering mechanics at Columbia University with a primary research focus in dynamics and structural vibrations. Prof. Smyth received his ScB and AB degrees at Brown University in 1992 in Civil Engineering and Architectural Studies respectively. He received his MS in civil engineering at Rice University in 1994, and an MS in electrical engineering (1997) and a PhD in civil engineering (1998) at the University of Southern California. He joined Columbia as an assistant professor in 1998. In 2007, he was a visiting researcher at the Laboratoire Central des Ponts et Chausées, Paris. He is the recipient of the ASCE Walter L. Huber Research Prize and was awarded an NSF CAREER award. He serves on the editorial board of the *ASCE Journal of Engineering Mechanics* and in 2011 was elected to serve on the Board of Governors of the ASCE Engineering Mechanics Institute of which he was named a Fellow in 2013. He also is a member of the Executive Committee of the US Panel on Structural Control and Monitoring. He serves as the chair of the Smart Cities Center at Columbia's Institute for Data Science and Engineering and is also the director of the Carleton Strength of Materials Laboratory at Columbia. Address: Department of Civil Engineering and Engineering Mechanics, 610 S.W. Mudd Bldg., MC4709, Columbia University, New York, NY 10027. E-mail: smyth@civil.columbia.edu